(NASA-CR-113609)   MAL OPTIONS FOR APOLLO 15   N79-71663
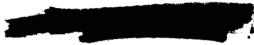LR3 ARRAY (Bellcomm, Inc.)   19 p

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SUBJECT: MAL Options for Apollo 15 $LR^3$ Array   DATE: August 14, 1970
Case 340

FROM: P. J. Hickson

Dr. R. J. Allenby -- NASA/MAL:

     I have reviewed the material relevant to your pending
decision on whether to fly an additional, perhaps expanded,
cube-corner laser ranging array on Apollo 15. The following
comments, focusing on the need for a third array, will show
that this review has not convinced me that the third array is
in any sense vital to the $LR^3$ experiment; it should merely
result in a modest science increment over the two-array experi-
ment. It is this modest increment that should be considered in
assigning the experiment priority vis-a-vis other flight candi-
dates. I will not discuss the latter, but concentrate on the
science value and rationale of the various $LR^3$ options.

     You will recall that, at your suggestion, I discussed
an earlier draft of this letter with the Lunar Ranging Experiment
(LURE) team members at their last meeting and requested detailed
quantitative reasons in support of their request for a third and
augmented array. The LURE team position, Reference 1, submitted
in reply, is not quantitative at all and limits itself to broad
and general, although very positive, terms. It shows that the
LURE team regards three deployed arrays as "essential to all of
the science that is to be obtained" by the experiment. This is
a new claim which has never been made before in any written form
and which remains unsupported by any, even qualitative, argument.
This claim, therefore, has never been examined by a NASA committee
and, given the complexities of the standard twenty-parameter
lunar theory, is not transparently valid. I have discussed the
LURE position paper in detail in the attached appendix, which also
includes a detailed list of the decision options available to you
and their rationale. I will list here only some comments and
conclusions.

1. Some modest science increment, mainly in the nature of
corroboration and confidence in the uniqueness of the
experiment solution, should accrue from emplacing a
third array; some advantage in reliability should accrue
if the third array is American rather than Soviet or
French.

2. The advantages of a large 300 cube array, at this time,
are unclear, unless it is to circumvent the present
(temporary) ground station difficulties. The augmented
array could more than pay for itself if it permitted,
in the future, use of much shorter laser-pulses; but
such laser hardware is not yet practicable (Reference 10).

3. The Cambridge Research Laboratory (CRL) ground station is not yet productive. Also, though the McDonald ground station now expects a couple of acquisitions on each of about six days a month, probably all in the first quarter, this does not provide enough data to be scientifically useful! (Kaula, Reference 4(a), page 2, has claimed once a week as the absolute minimum observation rate, so McDonald should not yet be regarded as "operational").

4. While a total of only 30 acquisitions have been reported so far, Dr. Mulholland has said that enough data has been collected over the lunar cycle to demonstrate that the Apollo 11 array works as expected and is undegraded by dust.

5. The CRL 1.5 meter (60") ground station should be at least as efficient as the McDonald 2.7 (107") meter ground station, i.e., provide about 25% returns under ideal conditions (see appendix). Note that at practical "seeing" levels the laser return signal scales directly as the square of the telescope aperture, so that a 12% return is expected with a one meter ground station, which appears satisfactory. Therefore, it seems clear that an augmented array is not required for operation with a one meter (40") telescope. In my view telescope guiding and astronomical seeing are much more important than telescope aperture for successful and reliable station operation.

6. The nub of the three-array proposal seems to be that three and only three arrays are needed to check fully the assumptions and results of the libration theory. The contribution of the librations to the range measurements must be eliminated to achieve the other scientific objectives. It is true that three Euler angles precisely define the orientation of a rigid body with respect to its center of mass (or three legs are needed for a three-legged stool), and that one set of three ground stations simultaneously monitoring one array, while two additional stations monitor the other two lunar arrays, could precisely define these angles as functions of time, independently of any lunar theory. But such precision is neither needed nor useful. In fact, we have a twenty-parameter lunar theory (Reference 8) in which most parameters, such as the moments of inertia, are used with six or more significant figures, exceeding any scientific interest. The $LR^3$ may add about two decimal places to each parameter, to fit the close experiment tolerances, but only the most careful and long-term analysis can determine how much to add to which physical constant. A third array should speed up this process, even improve the accuracy of certain constants

and our confidence in their new values.  But I seriously question whether the third array should therefore be considered essential.

7.  Only one lunar array, the Apollo 11 array, is required to achieve all of the earth applications and geophysics objectives of the experiment and to measure the lunar tides.  The Apollo 14 array appears necessary to determine the lunar librations and speed the data analysis, but very little new scientific knowledge should be expected, since, as Kaula points out (Reference 2), the lunar librations are already known well enough to determine the lunar mass distribution, whereas detection of a fluid core is not possible. After that about eight years of adding decimal places to the lunar orbit will be required before the relativity results can be extracted from the residuals. It would seem then that the actual contribution of this experiment to lunar science is remarkably modest and the priority of the third array, especially a large one, should also be very modest.

8.  The Apollo 11 and 14 arrays are separated 40 degrees in longitude and three degrees in latitude, so that their respective errors should be in the ratio of 3/40 and, in contrast I would be surprised at "tens of meters latitude error if one has to work with only two reflector information."  In fact, the above three degree separation in latitude is based on the assumption that the moon's rotation axis is a principal axis of inertia and hence the equator defines a principal reference plane of the libration.  This assumption is not in accord with Lunar Orbiter data analysis, and the true "latitude separation" is larger than three degrees.  The LURE position paper implies then, that the latitude separation of the arrays is vital to experiment success.  This would mean the possibility of a stronger $LR^3$ team requirement for site selection - a wholly new development.

Postscript:

The above letter and attachment were written to assess the LURE team position preliminary draft available (July 15, 1970). A final version of the LURE team position with a covering letter by Dr. J. Faller was transmitted to Dr. R. A. Petrone on July 30, 1970.  The position paper resembles the draft except for a few important points:

(a)  The statement that the third array is essential to all of the experiment science has been deleted.

(b)     The possible two reflector latitude errors have been
        altered from "tens of meters" to "several meters."

(c)     The dollar estimates of savings due to a large array
        have been deleted.

(d)     Paragraphs 6 and 7 give a sketch of the importance of
        polar motion and length-of-day measurements, couched
        in simple scientific terms, but no claims are made
        with respect to a third array or an enlarged array.

(e)     The statement "There are strong scientific reasons
        for placing the third retroreflector array on the moon
        at a location substantially away from the equator" is
        new and welcome.  The team position is now more logical,
        consistent, and focused.

(f)     In general the final position appears somewhat muted
        compared to the draft, but stronger and sharper.  There
        has been a perceptible shift to subnanosecond ranging
        as the main justification for the new larger array.

        The above changes are welcome in that they tend to agree
with some of the points I make in the letter and in the appendix.
However, I am transmitting my text unaltered since the substantive
position of the team has not shifted much from the draft position.

ORIGINAL SIGNED BY.

2015-PJH-gmr                    P. J. Hickson

Attachment
 Appendix

Copy to
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APPENDIX I

Contents

A.  Introduction

B.  Brief Review of LR$^3$ Experiment

    (a)   Objectives
    (b)   Observing Program
    (c)   Present status:  ground stations
    (d)   Present status:  science

C.  Dependence of Laser Return on Telescope Aperture

D.  Apollo 15 Array

    (a)   Arguments for a third array, discussion and comments
    (b)   Arguments for a large array, discussion and comments

E.  List of Options Available to MAL

APPENDIX I

A.  Introduction

The purpose of this appendix is to list the options available to MAL regarding an LR$^3$ array on Apollo 15.  Before arriving at this list we briefly examine the experiment objectives, array requirements, present status, and examine the claims made for the new array.  Section B is devoted to a brief review of the experiment, including its several objectives and the data needed for each, the planned observing program to supply these data and finally the present status of the ground stations and the science results.  Section C examines the functional dependence of the laser ranging return signal on the parameters of an enlarged array.  Section D lists the detailed arguments for a third array as well as for enlargement of its size and discusses each of these.  The list of options, ensuing from these considerations, follows in the closing Section E.

B.  Brief Review of the LR$^3$ Experiment

B(a) Objectives

The proposed objectives of the experiment are (Reference 4(a)) "(a) lunar size and orbit, (b) motion of the moon about its center of gravity, (c) geophysical information, (d) relativity experiments, (e) reckoning of Ephemeris Time, (f) landing site location; cartography; passive marker to aid in manned landings."  The basic experiment data is the precise range in light-seconds from an observing station to a particular corner array on the moon, with an accuracy of 1/2 part per billion, as a function of atomic clock time.  So far two permanent observing stations have been available.  Objectives (e) and (f) are applications, (d) comes very late and requires the (residuals of the) completion of (a) and (b).  Objective (c), terrestrial geophysical experiments, requires only one lunar array but several ground stations to measure the physical librations of the earth, Chandler Wobble, length of day, etc., and continental drift.  For continental drift measurements the mutual separations of many ground stations on every continent must be measured very accurately every year for many years, a very specialized and separate task, requiring only limited ranging opportunities and relatively modest ground facilities (no need to range in worst-case conditions).  All the objective (c) measurements need be made only at two (or three)

prime, well equipped, stations which will supply the continental drift stations with all array details and precise ranging (and guiding) predictions. A single enlarged lunar array would permit use of even more modest continental drift stations.

Objectives (a) and (b) study two substantially independent lunar motions (motion of the center of gravity and motion about the center of gravity) but these cannot be independently extracted from the single data parameter, range. The second lunar array, therefore, while not absolutely mandatory for experiment success, will obviously have a significant impact on the data analysis, in terms of ease, uniqueness, and credibility. The second station, by supplying in principle the capability for differential ranging, will make the achievement of objective (b) much more secure and by subtraction permit objectives (a), and hence (c) to be accomplished. A third array on the moon would undoubtedly add to the science return of the LR$^3$ experiment, but the increased return would clearly not be as substantive as the addition of the second array and would contribute only to objective (b) and not to the general solution of (a) and (c).

B(b)  Observing Program

When the prime ground station becomes operational, it is planned to range on the largest deployed array three times each day of the month (four hours before, during, and four hours after meridian passage) for about eight years (about 100 observations per month or ten times the current optimistic estimates of 12 to 15 per month). (Reference 4(d).) Ranging on the auxiliary arrays will be carried out two to four times per week depending on data needs (Reference 6). Kaula has considered the requirements for frequency of observation by laser tracking of the moon (Reference 4(b) page 2) and concluded that "the absolute minimum frequency of observation is weekly." Then he adds "tracking at the absolute minimum frequency of one night a week would only improve knowledge of the larger effects of more than $\pm 1$ meter amplitude: the lunar motion and libration. However, these phenomena are almost entirely gravitational and rigid body in their physics, and essentially less important than the variations in the earth's rotation, which involve less well understood material imperfections, ocean loading, and energy interchanges between atmosphere and crust or core and mantle. To contribute significantly to the solution of these latter problems, the laser ranging observing frequency must be nightly."

Note that the amplitude of the lunar tides is expected
to be about 0.4 m (Reference 2).

B(c)   Present Status:  Ground Stations

1.   The CRL station of Dr. D. Eckhardt at Tucson
acquired several good returns, all in five minutes on
September 2, 1969.  It has recorded no returns before or since.
The problems encountered by the CRL station include weather,
laser reliability, bad cavity design necessitating total
redesign and rework, a pending move to a new mountain top,
and an unresolved timing anomaly which puts an odd spike in
the range return histogram.  The station can fire 150 shots/
one day run and is now in the experiment debugging stage,
attempting to identify and resolve its major problems.

Dr. Bender questioned Eckhardt at length at the recent
LURE meeting and seemed to conclude that the CRL return
should be at least as good as McDonald, i.e., 25% under ideal
conditions.   (The CRL station has good beam divergence, good
timing hardware, a factor of two larger transmission for
its filter compared to the McDonald filter, an optical
efficiency. a factor of two larger than that of McDonald due
to fewer aluminum surfaces in the optical beam path, a col-
lector area which is one-third that of McDonald, and better
astronomical seeing.)  Seeing is okay.  "We don't need good
seeing, we just need good visibility."

I do not expect much real progress from CRL before 6
to 18 months, in any case, no science results but possibly
a real well-attested acquisition.

I would also note that the CRL station is a test case
for modest ground stations, for its entire capital cost is
only about $100 K.  Therefore, if the CRL station can be made
to work, it may never be necessary to use one meter (40")
telescopes for ground stations.

2.   The McDonald station of Dr. D. Currie at Fort Davis,
Texas, acquired about eight acquisitions in its first eight months
of operation, and at least one more in the month of June, 1970.
E. C. Silverberg, the LURE Project Scientist at McDonald, writes
(Reference 6, April, 1970) "In order to get better lifetime
from the rubies we have lowered the average laser power to
three joules."  "The Mulholland ephemeris only missed by about
300 nanoseconds on the recognizable acquisitions in April."
"As of a month ago I was beginning to make up contingency
plans for some drastic steps if we did not hit the corner
soon."  On March 15, 1970, the system was close to specifica-
tion and got 12% returns on 350 shots with 1-2 arcsec seeing.
On May 7, 1970, Silverberg writes "Prior to April 1 the laser

system had never acquired the corner reflector on more than one run on any one day.--- On the four days following April 12 we made eight definite acquisitions with one more possible. This is more data than we were able to recognize in the entire period from October to March with the Korad laser. ---primarily the result of new range tapes.--- Any improvement in the prediction ranges (down to the one microsecond level) will always be reflected in more data.--- The successes last month led the crew to anticipate an acquisition on any clear night when the seeing is three arcseconds or better." In June, 1970 one acquisition was reported, 3% returns at one arcsecond seeing (25 returns in 750 shots). On July 3, 1970 Silverberg writes "Certainly, most everyone expected that this first year would produce a lot more than 30 acquisitions." In estimating future data: "Using the first year as a guide, ---we might produce about 12 to 15 acquisitions a month on about six to eight separate days. I fully realize this is far below some of the other estimates made---." In the past estimate have always exceed results.

Regarding March 15, 1970, Silverberg writes "During the best run of 50 shots we had 1" seeing, 0.7% receiver efficiency and were putting three joules per shot into the telescope. We received 13 returns." i.e., 26% returns, a level never achieved before or since. Most returns are in the first quarter, and none is ever received between 9 a.m. and 3 p.m., a bad data distribution for science, below the Kaula minimum of one observation every week.

McDonald, therefore, cannot be considered "operational" as far as science data is concerned, and much more debugging, perhaps a year more, is needed before we start collecting useful results. The debugging should accelerate, since more trials can be made if some data is returned, but at the present low data levels debugging must be painfully slow. McDonald problems include weather, remarkably poor seeing (especially local seeing), laser reliability, range predictions, range tape truncation errors and tape read problems, computer guiding of telescope, optical alignment, optical efficiency, one-stop counter, pre-lase problems, etc. Currently the laser is shut down after five confirmed returns are reported, in order to save laser rods which are only good for about 4000 shots.

I do not believe that McDonald has completed its shakedown cruise yet, but Dr. Bender has remarked that only a factor of two improvement in McDonald return is likely, a factor of ten very doubtful.

B(d)   Present Status:   Science

At the recent AGU meeting in April, Dr. C. O. Alley repeated the same invited paper he had given one year earlier, before the Apollo 11 landing, save for one additional slide which reported about four acquisitions.

Data analysis so far has resulted in new coordinates for the Lick (and possibly also McDonald) ground stations, which differ by several meters from those previously available.  The scientific impact of these results is not expected to be large.  To my knowledge no further results have been reported to date and I would not expect much from the available data.

C.   Dependence of Laser Return Signal Strength on Telescope Aperture

The formula for the return signal (i.e., the number of photoelectrons received) in the LR$^3$ experiment is:

$$\text{return signal} = \frac{\text{constant} \cdot (Nu + 3Nc)D^2}{\theta^2_{\text{seeing}} + (\theta_{\text{laser}} \cdot \frac{D_1}{D})^2}$$

where   $\lambda$ = wavelength of ruby light, 694.3 nm

$D_1$ = diameter of laser oscillator rod, 19 mm

$D$ = diameter of transmitting-receiving telescope

$Nu$ = number of uncoated cube-corners reflectors in the lunar array

$Nc$ = number of silvered cube-corner reflectors in the lunar array

$\theta_{\text{laser}}$ = angular divergence (half-angle) of the laser beam leaving the laser rod

$\theta_{\text{seeing}}$ = the minimum angular diameter of a laser beam that has passed through the atmosphere, typically 12μ rad (2.5 arcsec)*

constant = includes all other effects such as the efficiency of photomultiplier, the laser pulse energy, normalization, thermal degradation of array, off-axis degradation due to librations, etc.

_____

*But generally worse at McDonald (see figure).

Note that for "large seeing" ($\theta_{seeing} > 2\theta_{laser} \cdot D_1/D$) the return signal scales directly as the square of telescope aperture, $D$, while for "small seeing" it scales as the fourth power of $D$.

For the following I will assume that the $LR^3$ experiment was designed to get a return 50% of the time (worst case) when a 150 cm (60") telescope and the Apollo 11 lunar array are used. For example, the CRL facility should achieve this performance. Then according to the above formula the McDonald 272 cm (107") telescope should have a return 11 times greater than the reference design, i.e., 100% returns. A 90 cm (36") telescope would have a return by a factor $(150/90)^4 = 7.9$ times smaller than the 150 cm telescope. Thus, a 90 cm (36") telescope can be used for ranging on the Apollo 11 array, but would get a return only 5.3% of the time during those worst-case conditions, when the 150 cm (60") telescope gets only a 50% return. An improvement of about 67% (for the worst case) is planned for the Apollo 14 array, by altering the recessing arrangements of the corners, so that a 90 cm telescope would get a return about 10% of the time (worst case) using the Apollo 14 target. A 10% return is probably marginal, except for a continental drift station where excellent range and guidance predictions are available and no search or preliminary acquisition problems are involved. It is, however, not clear whether continental drift stations should or would operate under "worst case" conditions. A 300 (uncoated) corner array should give a 30% return (worst case) for a 90 cm telescope, a more comfortable margin.

In the absence of hard experimental data from the two ground stations, the above numbers are only illustrative but appear to be realistic. These numbers appear also to be consistent with those of Dr. Faller, since he has suggested that a factor of five improvement in the $LR^3$ array (a factor of 1.7 improvement by recessing the corners and a factor of three by increasing the number of corners) would make ranging with a 90 cm telescope possible. The point I wish to emphasize here is that laser ranging to the Apollo 11 array with a 90 cm telescope is possible now and is certainly not precluded by any threshold process.

However, it may be found in actual operations that the signal return is critically low and too marginal for routine operation. In such cases the telescope guidance system may be more important than the size of aperture available, i.e., the number of usable 90 cm telescopes may be small. It is clear that continental drift studies could be usefully conducted in the remote Pacific where observing facilities (optical alignment, etc.) may not be optimum. Nevertheless, the proposal for a 300 corner array should be based on an analysis of the return signal margins now known to be available or projected, and an estimate

of the extent and frequency of observing, especially the worst-case ranging, required to perform the limited number of measurements needed for continental drift. Such analyses should be requested.

D. Apollo 15 Array

    D(a)  Arguments for a Third Array: Dr. J. Faller (Reference 1) Gives the LURE Team's argument as follows

A1: Fully check lunar librations theory, including free librations of the moon (Chandler Wobble) and effects of fluid core (emphasize full check so three and only three arrays needed)

A2(a): Apollo 11 and 14 arrays will not give good resolution on latitudinal motions (tens of meters errors perhaps), and two orders of magnitude increase in ephemeris accuracy is needed

A2(b): To reliably determine the geophysical and dynamical goals of the experiment

A3: May be able to discover free librations of the moon (Chandler Wobble) in three array data (see also A1)

A4: May make it possible to separate out and quantify the lunar tides

A5: "A third array is pertinent for and essential to all the science that is to be obtained"

    Comments on the reasons for a third array: as a general comment that the reasons are stated in very fuzzy non-quantitative terms, unsupported by any, not even qualitative, arguments. My specific comments are in the order of the arguments:

C1: I suggest that the sole purpose of the third array is the study of the physical librations of the moon. Dr. Faller has included in this the possible librations of a moon with a fluid core and the Chandler Wobble (force-free physical librations) of the moon. In his recent review article on the lunar gravitation field, a co-investigator, Professor Kaula (Reference 2), concludes that the libration parameters (C-A)/B and (B-A)/C (where A, B, and C are the lunar moments of inertia) are already known to $\pm0.1\%$ and $\pm2.5\%$ respectively, which appears to be "quite accurate enough to infer the mass distribution" of the moon. Kaula then mentions the $LR^3$ experiment as a source of improved libration data to determine if a non-rigid moon would have a perceptible effect on libration. He estimates the effect of a fluid core of half the lunar radius and finds it totally imperceptible. I conclude therefore that the lunar physical librations are a

solved problem for which the $LR^3$ experiment can provide only corroboration and therefore the additional precision obtainable by a third array (over the two-array measurements) is not warranted by its science return.

Now Kaula uses the libration data of Koziel who reviewed the free libration data and concluded "thus, for the time being, we can merely state that, for an observer on the Earth, the amplitude of the free libration in longitude is a quantity of the order of a few tenths of an arcsecond (0.5 µrad)." The free librations are invariably determined from the residuals of the forced-libration measurement and have not been adequately studied to date, but can probably be determined from the two-array measurements.

As to the accuracy of physical libration parameter measurements both the MacDonald article in the original Alley proposal (Reference 4(a)) and the CRL study by Julian (Reference 3) predict about two order of magnitude improvement following the use of two lunar arrays. Bender (Reference 7) predicts a similar improvement, but does not mention the number of arrays, which presumably does not exceed more than two. The Apollo 11 and 14 arrays are separated by only three degrees (100 km) in latitude, but I understand this is adequate (from $LR^3$ site selection requirements).

C2(a): Julian (Reference 3) notes that the latitudinal (and longitudinal) effects on the libration parameter errors are inversely proportional to the latitudinal (and longitudinal) separation of the two arrays. Thus the ratio of the latitudinal to longitudinal position errors should be 40/3. Dr. Bender (Reference 7) predicts that, after one year of ranging with 15 cm accuracy, the mean radius of the lunar orbit will be known to 25 m and the longitude with respect to perigee to to 0.04 µrad or 16 m. Thus latitudinal errors of "tens of meters" are expected in any case and will not be reduced significantly by a third array unless the third array is constrained to latitudes of about 20 degrees or greater.

C2(b): This argument is incorrect. The geophysics and earth dynamics of the experiment can be exactly determined using a single array on the moon and at least three simultaneously ranging earth stations. The orbit of the array need be known, only insofar as it is determined in obtaining the three ranges. With less than three ground stations some lunar theory is needed. This argument contradicts the published observation objectives. It is intended to range on the second and third arrays only a few times a week (Reference 5) which, by Kaula's criterion, can only give lunar libration and orbit data. Only nightly ranging on the second and third arrays will yield data that can influence the geophysical analysis.

C3:  As mentioned in Cl the free librations of the moon,
i.e., the librations described by Euler's equations of the
motion of a rigid body, but with the applied torque set equal
to zero, have not yet been "discovered" and would be of some
real interest.  Their Earth analogue, the Chandler Wobble,
clearly shows the non-rigid character of the earth since
their rigid-earth period should be ten months and their
measured period is 14 months.  The wobble is said to be cor-
related with earthquake production on earth.  The lunar
period predicted is about 1100 days, but the measured period
would be unknown, so the wobble would be hard to pick out of
the range residuals but is usually taken as being equal to
the libration residuals.  A third array, suitably placed (at
20° latitude), would clearly advance the wobble study, but I
do not think it would be essential.  On the other hand, the
wobble amplitude is unknown, but is expected to be small,
and the third array could turn out to be very useful.

C4:  Dr. Bender has noted that even earth tides, for example
M2, has shown a coast-to-coast continuity (i.e., their global
character) when local measurements are suitably corrected for
oceanic and atmospheric loading.  We expect then that lunar
tides, because of the extremely seismically-quiet moon, as
measured by the passive seismometer and predicted by the
absence of loading, could be inferred from a single station
measurement and clearly corroborated by two-array measure-
ment.  A third array would add little to lunar tidal study.

C5:  The essential character of the third array is apparently
related to the fact that three Euler angles are required to
specify the orientation of a body with respect to a space-
fixed set of axes with origin at the center of mass.  Yet
with a twenty-parameter (Reference 8) lunar theory this notion
may be somewhat naive, and indeed Dr. Mulholland explicitly
avoids this language.  Dr. Mulholland's ephemeris forms the
basis for the experiment, since the fundamental data are the
residuals from his predicted ranges.  I do not have his written
data analysis plan, but as I understand him he makes use of a
coefficient matrix for the deltas of the twenty parameters
from their established values, the residuals being fitted to
determine the deltas.  He then speaks of the third array as
necessary to guarantee that the matrix is not ill-conditioned
and hence acceptable solutions of low error are possible.
This explanation totally obscures or obviates the unique
character of the three-and-only-three argument.  The LURE team
did not supply an error estimate for the two-array experiment
and the three-array experiment as requested.

Faller and Wample agree that LR$^3$ theory is complex
(Reference 9).  "It is not obvious, however, how in this
procedure one can separate information about the moon from
information about the earth.  One can imagine, for example,

that some unexpected wobble in the earth's rotation (or
a movement of one of the surface plates) might be inter-
preted as a perturbation in the moon's motion. This is
not the place to explore how such possibilities can be
disentangled. Suffice it to say that good methods for
separating lunar from geophysical effects are believed to
exist. With data from four or more observing stations at
well-chosen locations, one can also separate local aberra-
tions such as continental drift from motions of the earth
as a whole."

I therefore conclude that the essential character of
the third array is not apparent and certainly has not been
demonstrated.

D(b) . Arguments for an Enlarged Array

Dr. Faller (Reference 1) has given the following
arguments for an enlarged, 300 corner, array (a return four
times larger than the Apollo 11 array):

A10: Astronomical seeing at McDonald is much worse than
anticipated and so the large array is needed if the bare
minimum of ten returns/month, evenly distributed, is to be
attained.

A11: International study of continental drift might be
greatly aided by the large array, since with its use smaller,
one meter, telescopes could get a reasonable rate of return.

A12: Savings of $300 K to $500 K per year on operation of
two primary and several secondary ground stations.

A13: Freeing of large 107" telescopes for other astronomical
observing tasks.

A14: Future use of subnanosecond pulses that would greatly
increase range accuracy (to a low of 2 cm perhaps).

A15: A third array has a higher priority than the Shapiro
Radio Beacon Experiment because of the limited life of the
latter and its optimistic accuracy claims.

A16: If an American array on the moon is not the biggest
and most reliable, and usable at all phase angles, then the
international observing program will use another, foreign,
array with the resulting loss in science leadership.

My comments:

C10: I agree that McDonald does not yet work as well as previously hoped for, but I believe we are still in the initial debugging phase and increased data rate and a more even data distribution is inevitable as experience is gained. Seeing is said to be really bad, but a low 3% return has been reported also on excellent days, so other problems, such as alignment and guiding, are not yet in hand (as the station log shows). I do not know what is wrong at McDonald, but I do not believe that only 30 returns, badly distributed, prove it will not work as needed. The Silverberg reports clearly suggest that I am not alone in this view and that improvements are expected. I do not believe that the McDonald ranging problems should be solved at the lunar end of the range. If hard data are available which proves that McDonald cannot be made to work, then these should be presented and the experiment feasibility reevaluated.

C11: Reliable return rate data are not yet available and the theoretical estimates, as in Section 6 above, do not indicate a need for a larger array to get an acceptable return rate on a one meter telescope. Note also that the CRL 1.5 meter station is so inexpensive (only $10 K for the 60" spherical metal mirror) that it would be unnecessary to tie up even a one meter optical telescope (which has a wide astronomical capability) to do the very specialized task of laser ranging. But again alignment and computer guiding are probably more important than aperture in achieving reliable station operation, especially at lunar night.

C12: Suggested savings are undocumented and perhaps illusory, but note:

(a) about ten years of savings at $300 K/year would just about pay for the expanded array, so a long-term financial view is necessary.

(b) little savings can be realized if argument 10 is valid and a large array is mandatory just to do the original experiment.

C13: I agree that other important observing tasks can be found for the McDonald 2.7 meter telescope (tasks which a "fly's-eye" or metal-dish cannot do).

C14: Very high power subnanosecond lasers are in operation today (Reference 10), but these are very large and developmental only, not observatory-type hardware. Thus it is not correct that faster timing means lower laser output, and the argument

which suggests we need a factor of <u>three</u> enhancement of the array because future possible laser developments may require it, is questionable. The point is a valid but very minor one, and should not be confused with the great advantages of the other faster timing experiment, when it becomes available and practicable.

<u>C15</u>: Valid in my opinion.

<u>C16</u>: Argument A16 is a valid point, but difficult to assess. The planned Soviet and French arrays are said to have a return about three times larger than the Apollo 11 array. The French optics are coated and so we expect that thermal degradation will entail some lost viewing, perhaps even ten days/month. The Soviet array is said to be coated but impervious to thermal distortion because of a remarkably low expansion coefficient over a remarkably wide temperature range. The reality of these plans, the reliability of the unmanned deployment, the reliability of the deployed array, the future cooperation of the foreign owner (who must tell us where the array is if we are to observe it), all of these points are held in some doubt by the LURE team members. Prudence suggests that if a third array is <u>needed</u>, it must be American to assure success. The leadership question is valid, though more programmatic and chauvinistic than scientific. It does influence morale.

E. <u>List of Options Available to MAL</u>

1. Not flying a third LR$^3$ array - I know of no detailed justification for flying a third LR$^3$ array in terms of its incremental science return.

Dr. Alley mentions in a recent proposal (Reference 5) that France will soon (November, 1970?) deploy a coated-optics cube-corner array on the moon so that a third array will be available for at least part-time ranging (assuming some solar/thermal degradation). Since the major libration contribution is from Earth, the resulting data loss, if any, (at solar frequencies) should not matter.

A reliability argument would not require a third array.

2. Flying a third array (on Apollo 15 or 16) - almost any array can be used by the prime stations, particularly McDonald, to improve the physical libration measurements, and additional science return should not result in terms of uniqueness and speed of analysis.

(a)   ten uncoated corners - such an array could be used
      by McDonald, but probably not by CRL

(b)   sixteen coated corners - should give a return about
      half that of the Apollo 11 array.  This array was
      suggested by Dr. Alley (Reference 5) as a possible
      marker at every landing site for cartography applica-
      tions, admittedly of low priority but perhaps cost-
      effective.  Coatings should now be considered, because
      of the Surveyor III camera experience, the reduced
      reliability constraints on an array, and the poten-
      tially large return possible.  A mix of coated and
      uncoated corners should be seriously studied.

(c)   one hundred uncoated corners (Apollo 14 array) - has
      an improved (67%) return over the Apollo 11 array, is
      already flight-qualified, so it may be cost effective.
      Coating, say, half the corners should double the return
      and provide low coating-risk, but may require thermal
      redesign.

(d)   two hundred uncoated corners (two Apollo 14 arrays) -
      the arrays can easily be deployed close enough together
      but it strikes me as a hard way to achieve a factor of
      two in signal return.  I understand this is the LURE team's
      back-up choice.

(e)   three hundred uncoated corners - return is only 50%
      above the 200 corner case which is therefore a better
      buy since it achieves the greatest relative improve-
      ment.  If 250 of the corners are coated, a factor of
      eight above the Apollo 14 array is obtained and a
      sunshade should improve daylight ranging.

(f)   10 cm coated berillium open corner - has not been
      proposed, but is ideal for ranging at any wavelength
      including that of a $CO_2$ laser.  Such a corner should
      be considered for development as having a wider future
      capability.  The return should be similar to the Apollo 11
      array and good thermal design may permit daylight
      ranging.

# REFERENCES

1. "LURE Team Position on a Third and Enlarged Laser Ranging Retro-Reflector Array," letter by J. Faller, July, 1970. This copy was marked by Col. Strickland as "PRELIMINARY DRAFT, revised copy will be available the week of July 20, 1970."

   See also a letter by Dr. J. Faller, Wesleyan University, to Dr. R. A. Petrone dated July 30, 1970, with an attachment entitled "LURE Team Position on a Third and Enlarged Laser Ranging Retro-Reflector Array", which is referred to in the postscript.

2. W. M. Kaula, Science, Vol. 166, December 26, 1969, p. 1581, "The Gravitational Field of the Moon," a review paper.

3. R. S. Julian, Technical Report AFCRL 66-503, June, 1966, "Feasibility Study of Laser Ranging Systems."

4. (a) Proposal for Laser Ranging to Optical Retro-Reflectors on the Moon, revised February 11, 1966, University of Maryland report by Alley et al.

   (b) Supplement to above, June 30, 1966.

   (c) Supplement II to above.

   (d) Supplement III to above, October 14, 1968.

5. Experiment Proposal (NASA form 1346), "Laser Ranging Retro-Reflectors, 'S-078'," by C. O. Alley, November 17, 1969.

6. University of Maryland, Technical Request N° 70-106, "Report on Lunar Ranging at McDonald Observatory for the Period February 16 to April 15, 1970," by Douglas G. Currie, April, 1970.

7. NASA SP-214, Apollo 11 Preliminary Science Report, p. 164.

8. Dr. Bender lists 17 parameters and I have added three more, the Euler angles between the reference and principal axes of inertia. Each array adds three more parameters.

9. J. E. Faller and E. G. Wampler, Scientific American, Vol. 222, March, 1970, p. 49.

10. Letter dated August 5, 1970 to P. J. Hickson by S. L. Penn, Bellcomm, "High Energy, Subnanosecond Laser Pulses."